Key Specifications for Tevatron BPM Hardware Architecture Choices

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Introduction

- The system will focus on the 53 MHz fundamental component of the beam current to determine position.
- Linearity is one of the more difficult requirements for the system to meet.
- Must measure closed orbit positions of protons and pbars with both species present in the pickup.
- Must insure that the system maintains its resolution throughout the sampling and processing path.

Why 53 MHz component?

- Need to focus on a frequency that doesn’t have a magnitude null for some arbitrary Tevatron filling pattern.
- RF system operates solely at 53 MHz with no visible change plans.
- Consequently, 53 MHz signal is only a function of total beam intensity and bunch width (will vary by factor of 2 as bunch narrows through the ramp).
- DC component would be better, but BPMs do not have any DC response.

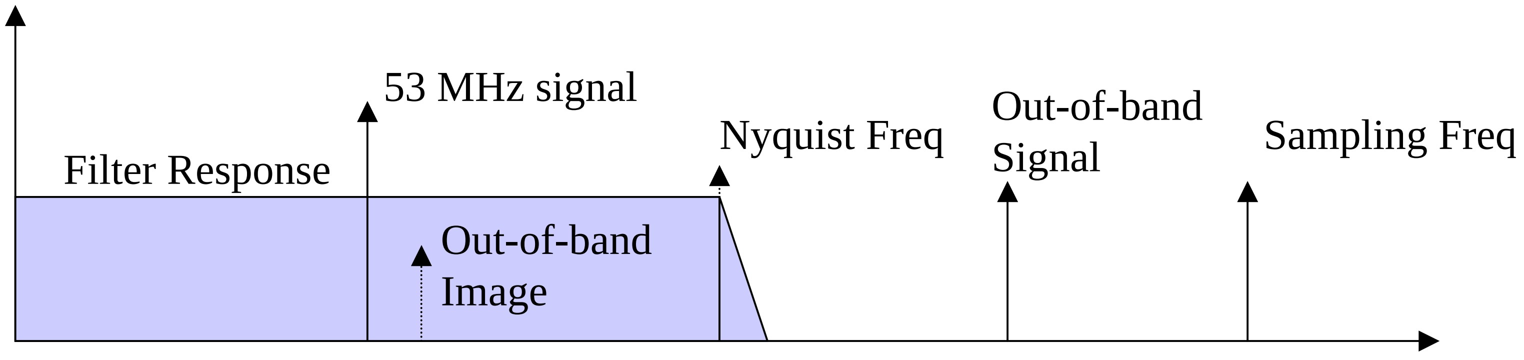
Linearity

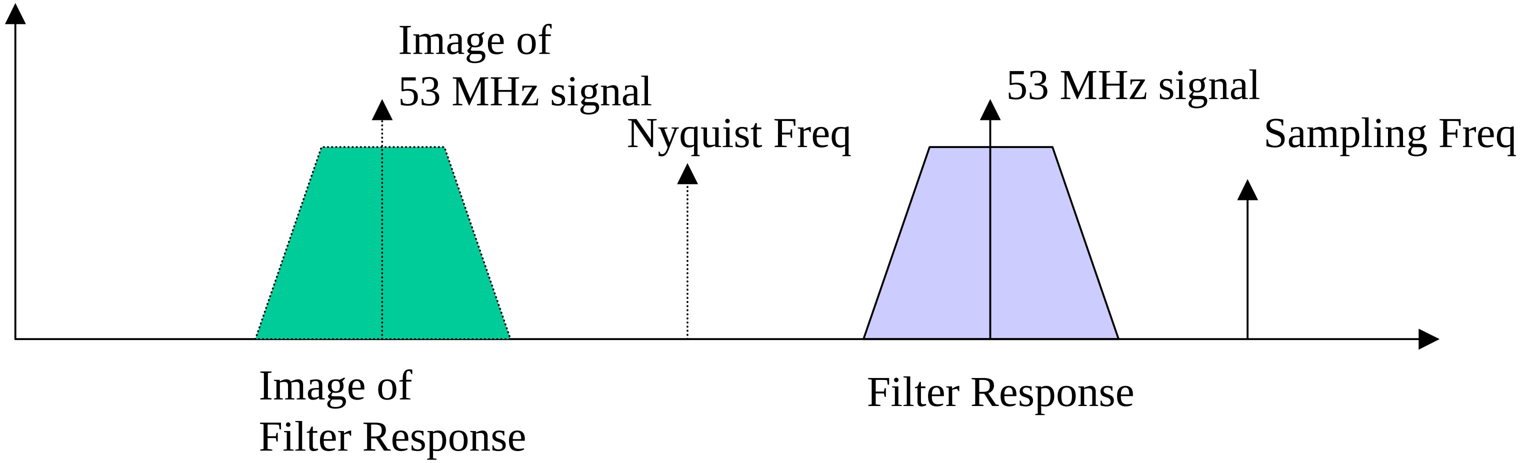
- In order to meet the 1.5% linearity requirement, the system must have a 40dB linear dynamic range.
- This precludes the use of most analog active devices upstream of the digitizer, especially analog mixers (3rd order intermodulation term in most mixers not better that 20dB).
- Without frontend mixers, the digitizers must digitize the 53 MHz component of the beam directly.

Sampling 53 MHz component

- Sample above Nyquist frequency (>106 MHz) and analog filter higher frequency components that can alias into passband.
- Sample below Nyquist frequency (60 MHz < sample freq < 85 MHz) and analog bandpass filter components that can alias into passband. Image of 53 MHz component will be translated to new frequency (sample freq – 53 MHz).
- Filter must reduce all images that could interfere with 53 MHz component by 65dB to meet resolution requirements.

Sampling 53 MHz component





Signal to Noise and Distortion

$$rmsposerr = R\frac{A_{err} - B_{err}}{A_{sig} + B_{sig}} \cong R\frac{\sqrt{2}A_{err}}{2A_{sig}} = SINAD \frac{R}{\sqrt{2}}$$

R = 26mm

For rms position error better than 33μm, SINAD better than 55dB.

For rms position error better than 7μm, SINAD better than 69dB.

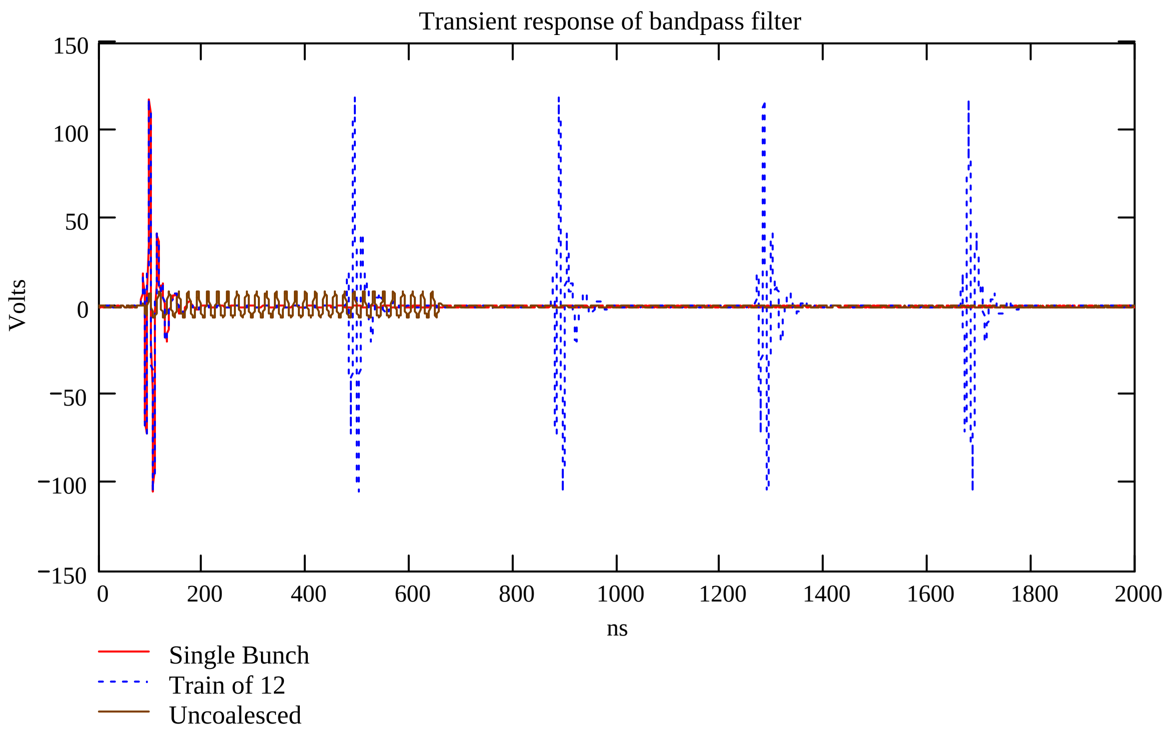
Digitizer Specifications

- Digitizers with at least 14 bits usually have SINAD better than 72dB for a single sample.
- We achieve better SINAD by averaging multiple samples of a single bunch (whether by fast sampling or stretching the bunch signal out in time with analog filters).
- SINAD is directly proportional to signal level. We must carefully monitor our dynamic range of the signal.

Signal Dynamic Range

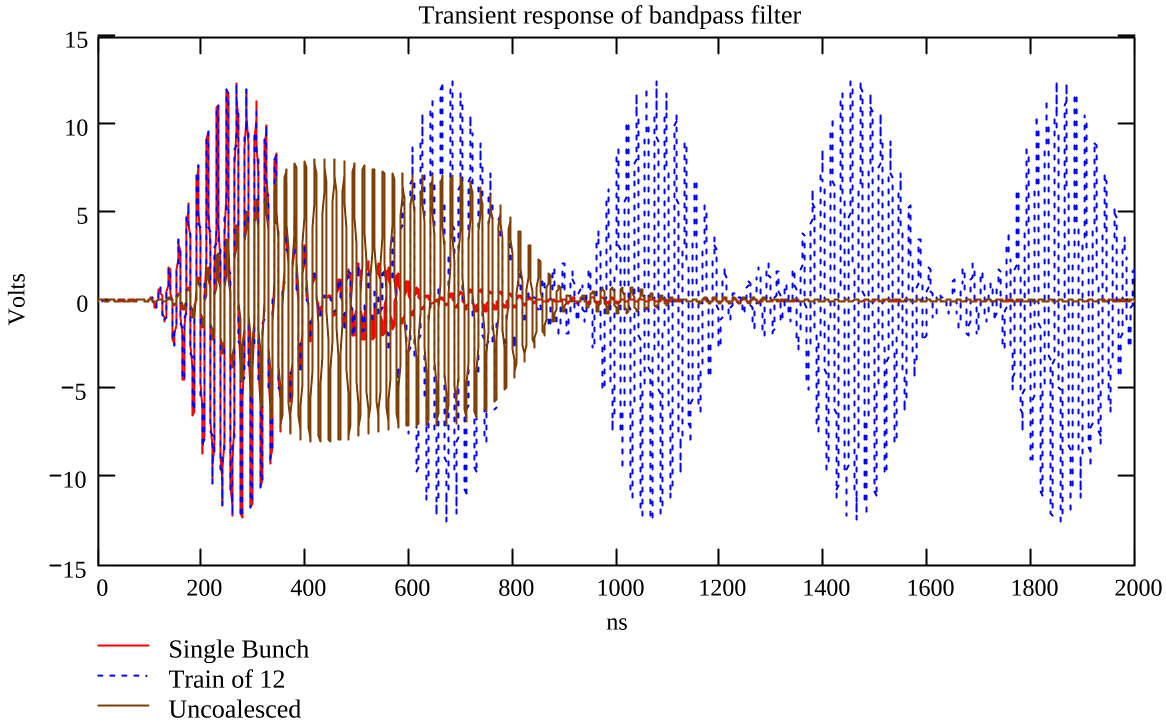
- Try to reduce the dynamic range seen by the digitizers to maximize SINAD.
- Variable gain amplifiers introduce non-linearity (and calibration errors) into the system.
- We can reduce total dynamic range for common operating conditions with proper analog filters.
- We have a minimum dynamic range of 6dB due to change in 53 MHz component of beam as beam gets narrower up the ramp.

Signal Dynamic Range



Plot showing the transient signal seen by the digitizers after a 50 MHz wide bandpass filter centered at 53 MHz. The three traces represent single bunch, train of 12 bunches and 30 uncoalesced bunches at 980 GeV.

Signal Dynamic Range



Plot showing the transient signal seen by the digitizers after a 5 MHz wide bandpass filter centered at 53 MHz. The three traces represent single bunch, train of 12 bunches and 30 uncoalesced bunches at 980 GeV.

Benefits of Narrowband Analog Filter

- Keeps dynamic range low over different operating conditions.
- Allows more samples of the bunch improving the SINAD through averaging.
- Makes the comparison of uncoalesced bunch positions and coalesced bunch position more consistent for better tuning reliability.
- Disadvantage: Interference of signal from bunch to bunch for 2.5 MHz spacing.

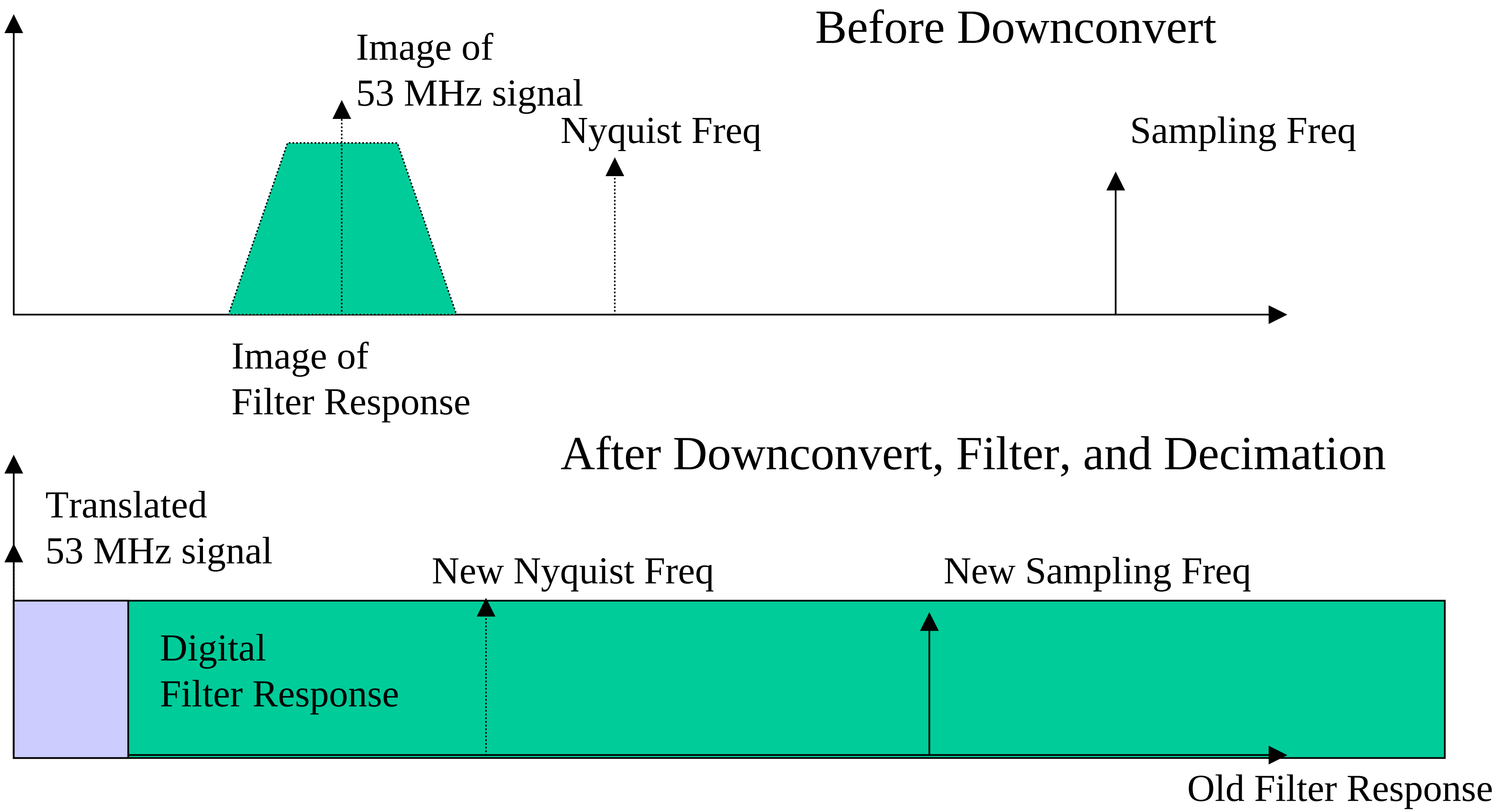
Downconvert and Decimate

- Impossible to get raw data from digitizer through a backplane data bus at the digitizer sample rate. We need to reduce the data rate.
- We are interested in the power around the 53 MHz component of the beam frequency over a narrow bandwidth.
- Take the digitized data and multiply the data by the function $\cos(\omega t)$ where ω is the 53 MHz RF frequency, or the image of the RF frequency after undersampling.
- This translates the power in the 53 MHz line from an intermediate frequency to DC.

Downconvert and Decimate

- After frequency translation, the signal is digitally filtered to desired bandwidth.
- This bandwidth is much smaller than the original analog bandwidth. Having this data represented at the digitizer sampling rate is grossly oversampled.
- The data can be decimated to a rate that a processor can handle without losing any information in the new signal bandwidth.

Digital Downconvert and Filter



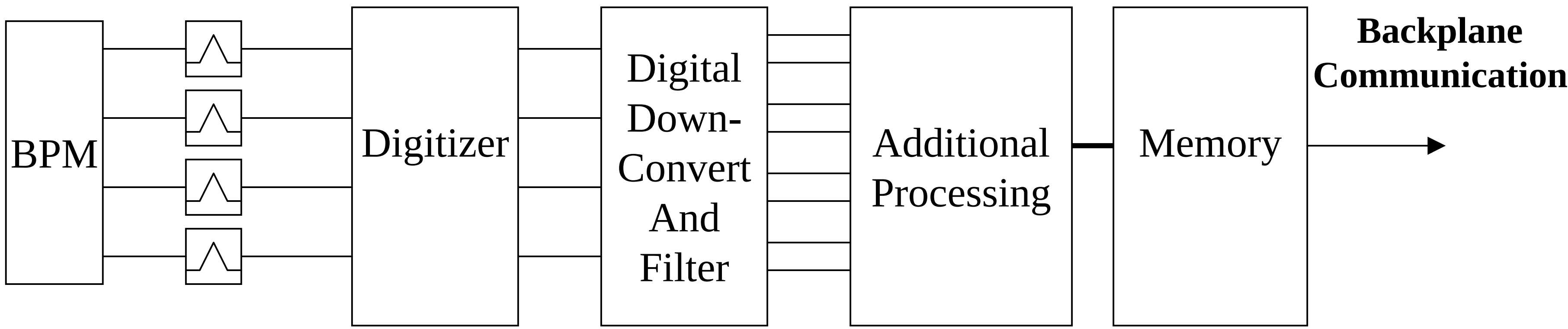
Process Gain

- It is important to preserve the SINAD through the digital filtering process.
- A single bunch produces a spectrum that has equal amplitude signals at all of the revolution harmonics over the bandwidth of the analog filter.
- The digital filter allows only one revolution line to pass. The signal is reduced by the number of revolution lines contained in the passband of the analog filter.
- An analog filter with a bandwidth of 5MHz contains about 100 revolution lines.

Process Gain

- To preserve the SINAD of the digitizers, the digital filter must have enough extra bits to drop the noise floor with the loss in signal.
- For the example of the 5 MHz passband, the noise would need to drop by about 40dB. The filter would need 8 more bits than the digitizer to preserve the digitizer SINAD.

Basic Hardware Architecture Skeleton for Data Path



Measuring Pbar Closed Orbit in Presence of Protons

- Need to measure around the ring.
- Pbar-proton time spacing is not conducive to time differentiation around the ring for all cogging values.
- Find a solution for measuring pbars that doesn’t compromise proton position resolution.

Pbar Signal De-embedding

- De-embedding process similar to cross-talk calibration in network analyzers.
- Focuses on frequency resolution instead of time resolution.
- Takes advantage of linear, time-invariant property of passive systems.
- Works with narrow analog bandwidth and does not force the analog frontend to include switches and amplifiers when changing from coalesced mode to uncoalesced mode.

Linear Time-Invariant Systems

- The hardware for the BPM system up to the digitizer is composed of passive components (striplines, cables, lumped element filters). This makes the system linear time-invariant (LTI).
- LTI systems have the property that when vin(t) produces vout(t) and Vin(t) produces Vout(t) then a*vin(t) + b*Vin(t) produces a*vout(t) + b*Vout(t) (superposition).
- They also have the property that vin(t-τ) produces vout(t- τ) (time-invariance).

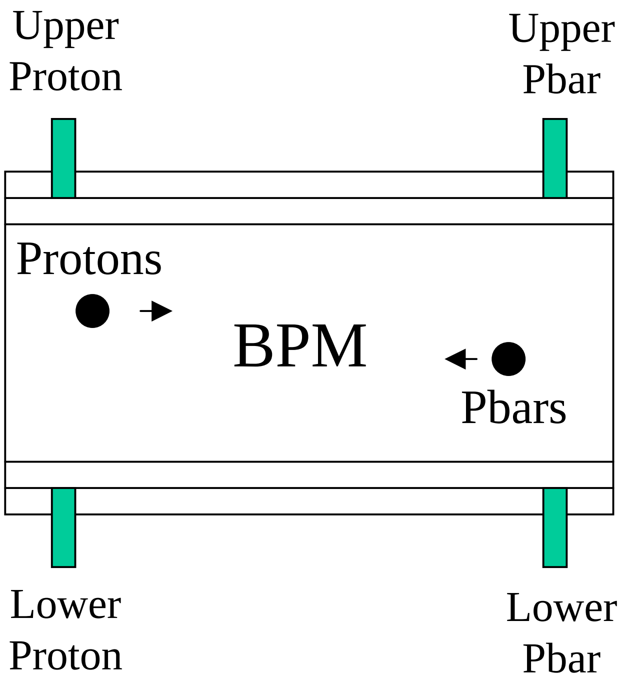
Linear Time-Invariant Systems

- Superposition implies that the output can be constructed by separating and summing its response to different independent sources.
- Time-invariance and superposition make exponential functions eigenfunctions of the system. This means that different frequency components don’t mix.

Separation of pbars and protons

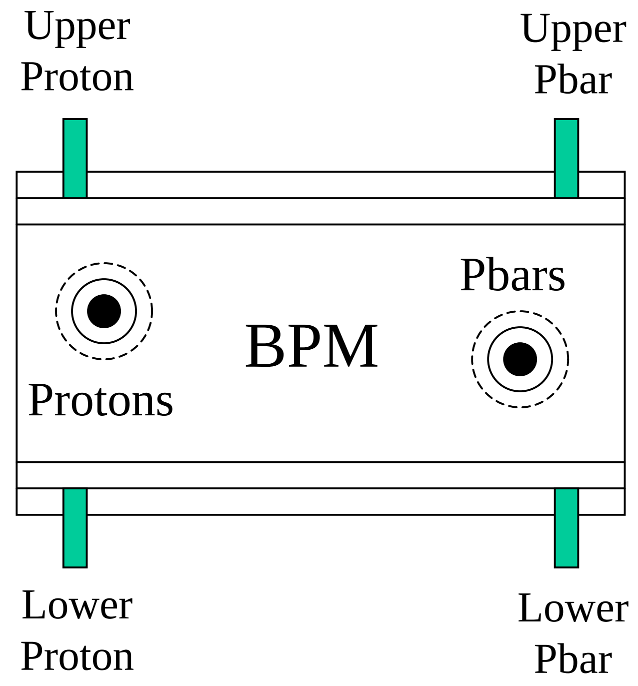
- Proton and pbar signals are linearly independent sources.
- Output signals can be deconstructed into pbar and proton components.

$$V_{xin} = V_{xin,prot} + V_{xin,pbar}$$



Two fixed transmitter sources

- Imagine two fixed location transmitters radiating inside the BPM.
- All signals are LTI and everything works ideally.

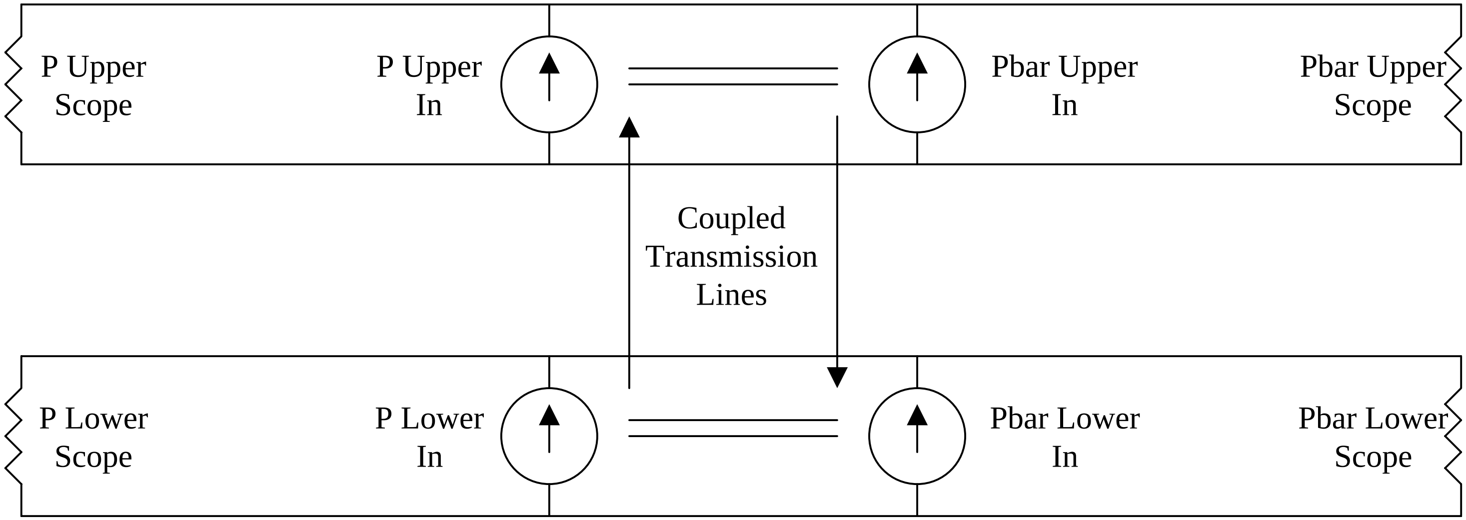


Solving for pbar only term

- Solve for the pbar component of the signal on the pbar pickup.
- Pbar component is a linear function of the total signal from the pbar plate and the total signal from the proton plate.
- Technique relies on the stability of the proton component calibration ratio as a function of position.

$$V_{upbarout,pbar} = \frac{V_{upbarout} - \dfrac{V_{upbarout,prot}}{V_{uprtotout,prot}} V_{uprotout}}{1 - directivity^2}$$

Transmission Line Model



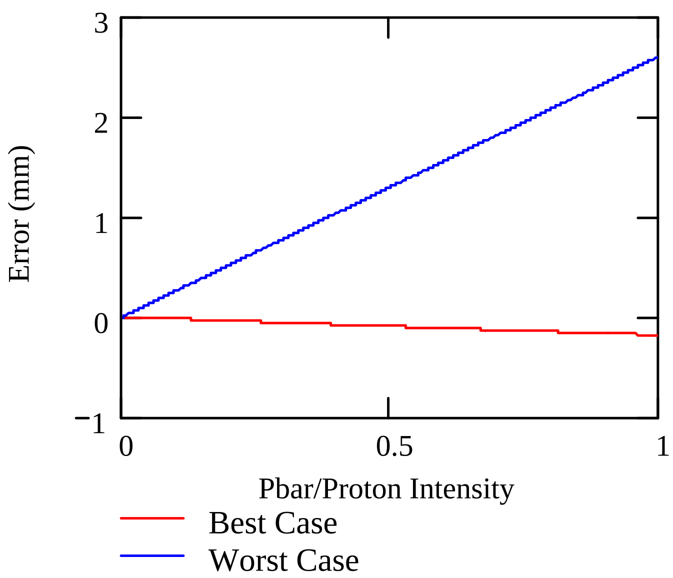
Non-idealities in Linear Process

- Coupling between BPM plates creates non-linear relationship between proton-pbar signal ratio and position.
- Unmatched transitions and terminations corrupt symmetry for coupling analysis.
- Beam angle through BPM could change, affecting ratio of beam signal seen at pbar end of pickup relative to proton end.

Pbar Position Measurement Options

- Ratio of pbar signal to proton signal on a single plate stable enough as a function of beam position for operational requirements.
- Solve for independent eigenvectors whose eigenvalues are linear functions of beam position (some kA+B).
- Calibrate system with protons only on desired proton orbit (uncoalesced) immediately prior to measurement of pbar orbits.
- Have separate time differentiation processing modules placed at a subset of locations around the ring for measuring pbars. (Enough to verify proper separation).
- New paradigm for BPM processing using large front-end analog bandwidth and time differentiation of proton & pbar signals.

Effect of High Intensity Pbars on Proton Position



Plot showing the effect of pbars on the proton position measurement. The best case scenario means that the directivity of the A plate is in phase with the directivity of the B plate. Worst case is the directivities are counterphased.

Other Specifications

- Digital filter must be capable of 10Hz resolution bandwidth, so that position variations due to synchrotron motion is averaged out.
- The system needs to handle position samples from each BPM (protons only) at a rate of 47 kHz for up to 8196 samples. This is the turn-by-turn requirement.
- The system must be capable of continuous closed orbit measurements at a 500 Hz rate (except when doing turn-by-turn measurements).

Summary of Hardware Specifications

- De-embed proton and pbar signals using crosstalk calibration.
- Use narrowband analog front-end filter centered at RF frequency.
- Undersampling is acceptable for narrow analog bandwidth.
- Use digital down-convert techniques.